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S. Krishna Kumar
Indian Institute of Technology Madras, India

A. Boominathan
Indian Institute of Technology Madras, India

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SITE SPECIFIC SEISMIC ANALYSIS OF A DEEP STIFF SOIL SITE

Krishna Kumar S
Indian Institute of Technology Madras
Chennai, India 600 036

Boominathan A
Indian Institute of Technology Madras
Chennai, India 600 036

ABSTRACT

Site specific analysis was carried out for a deep stiff soil site located near Ahmedabad, India. The site predominantly consists of sandy clay and silty sand layer in the top 30m with V_s varying from 430 to 750m/s. It is followed by a high plastic stiff clay layer cemented with sand and gravel with unusually high V_s above 1000m/s. The study region surrounded by 13 major faults has experienced several major earthquakes including the disastrous Bhuj earthquake (Mw=7.7). The seismic hazard level at the site was estimated by deterministic approach and the East Cambay fault with Mw of 6.2 is found to be the controlling source capable of causing a surface PGA of 0.46g. 1D ground response analysis carried out using SHAKE 2000 and DEEPSOIL reveals an amplification of the ground with a surface PGA of 0.52g and 0.43g respectively. The design response spectrum obtained by RRS analysis was compared with several contemporary seismic design codes. It is found that the seismic provisions tend to under estimate the spectral acceleration by about 30% at mid period range. The maximum spectral acceleration compares well with those observed at similar deep stiff soil sites at Los Angeles reported by Chang et al (1997).

INTRODUCTION

The ground response to a seismic excitation depends predominantly on the local site characteristics. The variations in the upper geological formations profoundly influence the characteristics of the earthquake motion on the ground surface. The seismic response of deep soil deposits having thickness in the order of 100 - 1000 km is unique and complex. Limited studies have been carried out on the responses of the deep stiff soil sites to seismic excitations (Chang and Bray, 1995; Park and Hasahash, 2005). Chang et al (1997) observed that the deep soil deposits are capable of generating considerable spectral acceleration for long period ground motion. Deep soil sites have high strengths and are capable producing sustained high accelerations at stronger levels of shaking. Thus it is particularly important to understand the response of such deep soil sites as they are more common throughout the world. This paper attempts to provide an insight in to the seismic response of such sites. In the present study a site specific analysis involving seismic hazard and ground response analysis was performed for a seismically vulnerable deep stiff soil site near Ahmedabad, Gujarat.

The deterministic approach is adopted to estimate the ground shaking hazard and 1D Ground response analysis was performed using discrete point and pressure dependant models to predict the ground surface motions. The results of the site specific analysis are compared with the contemporary codes and available predictive relationships.

SITE DESCRIPTION

A deep stiff soil site located about 12km from Ahmedabad, Gujarat (India) along the banks of Sabarmati River is considered in the present study. The Sabarmati river basin is characterized by the presence of 300-500m thick overburden soil. The site is located in the seismically active western coastal region of India, which has experienced several major earthquakes including the disastrous Bhuj earthquake, 2001 (Mw = 7.7). Severe damages to multistory buildings were recorded in close proximity to Sabarmati river area in Ahmedabad during 2001 Bhuj Earthquake (Sitharam and GovindaRaju, 2004). The site is categorized under Zone III as per Indian seismic code (IS 1893-2002). Various types of multi-storied buildings are proposed in the site which spreads over 500 acres of land. The seismic vulnerability of the region and presence of deep soil necessitates performing site specific ground response analysis to arrive at the design ground motion parameters.

SITE CHARACTERIZATION

The study region located on the Sabarmati River basin is characterized by quaternary soil deposit with Mesozoic rocks over thrusting them (Rastogi, 2001). It is located in the Cambay rift flanked by the east and the west Cambay faults. The Cambay rift basin in northwestern India is one of the pre-continental rifts that originated between the early Jurassic and Tertiary, after the breakup of Gondwanaland. The basin is covered by thick layers of Quaternary and Tertiary sediments, occurred during the Cenozoic period (Biswas, 1987). Refraction and deep seismic sounding studies established the thickness of the Quaternary and Tertiary sediments in most parts of the basin to vary between 3000 and 5500m (Kaila et al, 1981, 1990). The top 300-500 m is characterized by quaternary deposits (Tewari et al. 1995; Rastogi et al. 2001).

Standard Penetration Tests (SPTs) were conducted up to a depth of about 60 to 80 m at 150 locations in the site. The water table is encountered at a depth of 30 m below the ground level. The top 2.5 to 4.0 m layer is characterized by clayey sand (SC) with SPT ‘N’ value varying from 30 to 40. Silty sand (SM) and clays of intermediate plasticity (CI) are also observed in the top layer at certain locations. It is followed by a 25 m thick sandy clay layer with high SPT ‘N’ value varying from 60 to 100. A very thick clay layer with sand gravel mixtures is encountered 30 m below the surface level which extends to the borehole termination depth of 60 m. The SPT ‘N’ value in this layer is significantly greater than 100. The laboratory tests conducted on soil samples collected at this layer reveals plasticity index values of above 30. The unconfined compressive strength of this layer varies from 360 to 380 kPa, indicating hard consistency of the clay. The consolidation test carried out on the above soil samples shows low compression index values less than 0.06 confirming the presence of hard clay stratum. In general the soil strata at the site have a very high strength and stiffness, although rock formations are not encountered within the depth of investigation. A typical bore log of the site is presented in Figure 1.

Cross hole tests were performed at 28 locations in the site as per ASTM standard 4428 M-84. The test was conducted using three 150 mm size boreholes: a source borehole and two receiver boreholes each spaced 3.0 m apart. The cross hole tests were performed at an interval of 1.5 m up to a depth of 60.0 m. Figure 2 shows a typical variation P-wave and S-wave velocity with depth. The measured shear wave velocities were used as an input to the site specific analysis.

SITE CLASSIFICATION

Local site characteristics profoundly influence the response of the ground to a seismic excitation. The site classification generally gives an idea about the seismic response of a particular site. Several contemporary codes considers site

Depth	Notation	Soil Description	SPT 'N'
0.00		**0.00 to 4.80 m**	-
1.50		Brownish,fine to very fine grained, clayey sand	-
3.00		with much gravels (SC)	38
4.50			-
6.00		**4.80 to 15.80 m**	69
7.50			-
9.00		Reddish brown and greyish, fine to very fine	>100
10.50		grained, sandy clays of intermediate plasticity	-
12.00		with occational gravels (CI)	>100
13.50			-
15.00			-
16.50		**15.80 to 26.50m**	-
18.00			73
19.50		Yellowish brown, fine to very fine grained,	-
21.00		sandy clays of high plasticity with little gravels	100
22.50		(CH)	-
24.00			84
25.50			-
26.50		**26.50 to 28.90 m**	
27.00		Yellowish brown, fine to medium grained,	>100
27.50		clayey sand (SC)	
28.50			-
29.00		**28.90 to 31.60 m**	
29.50		Yellowish brown, fine to medium grained, silty sand with little gravels (SM)	
30.00			-
31.50		**31.60 to 34.50 m**	-
33.00		sandy clays of high plasticity (CH)	>100
34.50		**34.50 to 40.00 m**	-
36.00		Brownish, greyish, fine to very fine grained, clay	>100
36.50		to very fine grained,	
37.50		clayey sand with some	-
39.00		gravels (SC)	-
40.00		**40.00 to 46.50 m**	
40.50		Reddish brown, fine to very fine grained, sandy	>100
41.00		clays of intermediate plasticity with little gravels	
42.50		(CI)	>100
43.00			
45.00			-
46.50		**46.50 to 50.00 m**	
48.00		Yellowish brown, fine to very fine grained,	>100
48.50		clayey sand with some gravels (SC)	
50.00			-

Fig. 1. A typical borelog of the site

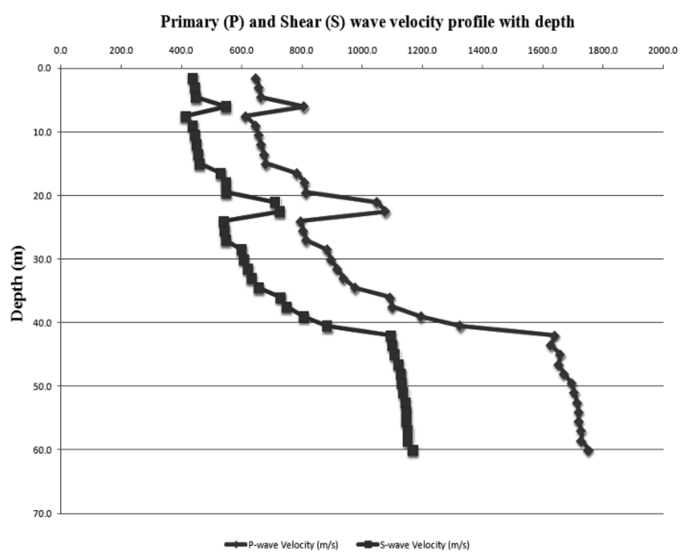


Fig. 2. Typical variation of P- and S-wave velocity with depth

effects by lumping groups of similar soil profiles together so that their provisions apply to broad ranges of soil conditions within which the local conditions of a particular site are expected to fall (Carlos et al 2006). Site classification based on average shear wave velocity of the top 30m is the most widely employed method for site classification.

The average shear wave velocity for the upper 30m computed using the cross-hole test data varies between 400m/s to 600m/s and is classified as C class site (Dense soil / soft rock) as per NEHRP seismic design provisions (BSSC, 2001). Only very few locations the average shear wave velocity in the top 30m exceeds 750m/s and hence are classified as B class site. The above site classifications are used in the seismic hazard analysis to consider approximately the site effects. Eurocode 8 classifies the site as predominantly B class having deposits of very dense sand, gravel or very stiff clay, at least several tens of m in thickness, characterized by gradual increase of mechanical properties with depth. Dickenson and Seed (1994) proposed a site classification for seismic site response. The site is classified as C3 as per Dickenson and Seed (1994), this classification considers both the shear wave velocity and the thickness of the soil strata. The site is described as a deep stiff cohesive soil with a mix of cohesionless soil.

SITE SPECIFIC ANALYSIS

The significance of the local site effect on the earthquake-resistant design must be accounted for by the development of site specific design ground motions i.e. motions that reflect the levels of strong motion amplitude, frequency content and duration of the structure or facility at a particular site. Hence site specific design ground motion estimation should include both seismic hazard analysis and ground response analysis.

Seismic Hazard Analysis

Seismic hazard analysis involves the quantitative estimation of the seismic hazard at the site. In the present study earthquake potential of each fault was evaluated by deterministic approach considering the faults and lineaments that lie within 250 km radius of the study area. Thirteen earthquake sources were identified within 250km radius of the study area utilizing the seismotectonic atlas of India (GSI 2000). A base map was prepared incorporating the earthquake sources using the Geographic Information System (GIS) platform Arc GIS 9.2 (Figure 3). The earthquake data during 1668 to 2008 were collected from various sources such as IMD, USGS, GSI, ISR, ISC, and GERI which includes details on time of occurrence, location, depth, magnitude and intensity. These earthquake details were mapped onto the faults based on the location and depth of the earthquake and the length of the fault as shown in Figure 4. This information is utilized while assigning the maximum magnitude for each fault source by considering the seismicity around the particular fault source. The maximum magnitude for a particular seismic source was taken as the largest observed past magnitude plus 0.5 (Kijko and Graham, 1998; Sokolov et al. 2001). In the present study the epicentral distance from the source to the site is considered as the shortest path.

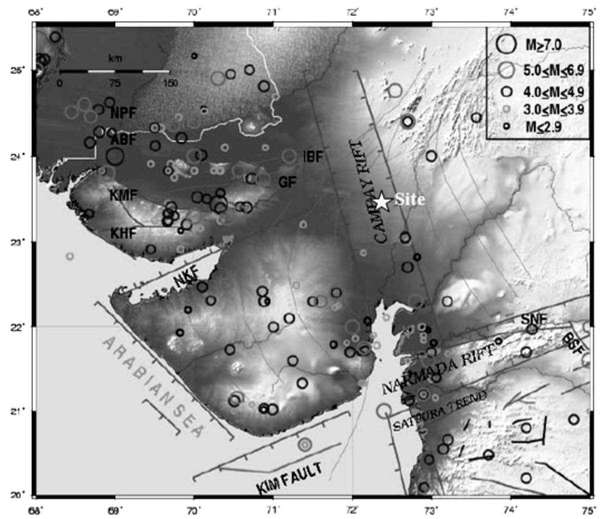


Fig. 3. Base map of the study region

The predictive relationship should characterize the source, travel path and the site conditions. The site considered is prone to intra-plate earthquakes, hence the PGA value at the surface is estimated using the predictive relationship proposed by Frankel et al (1996). The crustal intra-plate relation developed is for the site condition specified as the boundary between NEHRP classes B and C, having an average shear-wave velocity of 760 m/s in the top 30 m. The study area considered also have an average shear wave velocity of about 800m/s in the top 30m, justifying the use of Frankel attenuation relation. Cramer and Wheeler (2001) observed that the crustal intra-plate relation of Frankel et al. (1996) yields ground motions similar to the strong ground motion data recorded from the 2001 earthquake at large distances (Peterson et al. 2004). The Frankel predictive relationship yield a PGA value of 0.14g close to the actual recorded PGA of 0.106g at Ahmedabad during Bhuj 2001 earthquake (Hazarika and Boominathan, 2009) for a magnitude of 7.7. As the Cambay rift region is more susceptible to shallow focus earthquakes, a focal depth of 15km was adopted. The controlling earthquake that is expected to produce the strongest level of shaking is obtained by plotting the variation of peak ground acceleration with distance for different sources. The PGAs value obtained adopting Frankel attenuation equation for different sources are presented in Table 1. It can be observed from Table 1 that the East Cambay fault located at a distance of about 20.5 km from the site is the controlling earthquake source capable of producing a maximum PGA of 0.46g for a magnitude of 6.2.

Table 1. Estimation of PGA

Fault	Moment Magnitude (M_w)	Distance from site (km)	PGA (g)
East Cambay Fault	6.2	20.5	0.460
West Cambay Fault	5.1	15.7	0.110
West Coast Lineament	5.5	100.3	0.030
Island Belt Fault	6.1	130.0	0.024
Katrot Bhuj Fault	6.5	236.5	0.016
Kutch Mainland Fault	8.3	169.5	0.140
North Kaitwar Fault	4.9	95.0	0.007
Chambal Jamnagar Lineament	6.2	100.0	0.027
Kim Fault	4.3	292.0	---
Son Narmada Fault	5.1	207.5	0.003
Tapti North Fault	6.2	230.7	0.006
Paldi Fault	5.9	141.5	0.016
Allah Bund Fault	5.6	255.0	0.004

<u>Ground Response Analysis</u>

Local site conditions profoundly influence the characteristics of the surface motion; the extent of the influence is predominated by the topography and material properties of the stratum. Ground response analysis can be performed either using 1D or non linear models. The uniformity of the soil strata throughout the study region and its locations on the central region of the basin justifies the use of 1D model for ground response analysis in the present study. 1D ground response analysis based on equivalent linear analysis was performed using the widely adopted SHAKE2000 program (Shake 2000). The equivalent linear procedure adopted uses an iterative procedure to consider the nonlinear variation of shear modulus and damping properties of the soil defined by discrete points. The soil curves to be adopted can also be defined by hyperbolic models. The modified pressure dependant hyperbolic model developed by Konder and Zelasko (1963) incorporates two additional parameters to define the soil curves based on the confining pressure, however coupling between the confining pressure and shear stress was not considered. In the present study the coupling is considered by making the reference strain confining pressure dependant (Hahash and Park, 2001).

In the present analysis a strong motion data recorded in a site with identical seismic and site conditions is used as the input acceleration time history. The input acceleration is obtained by scaling the strong motion data recorded during the 1999 Chi-Chi earthquake under similar seismic scenario to a required PGA of 0.46g as estimated from the DSHA. The surface acceleration time history is presented in Figure 4. The Fourier spectrum for the adopted input motion shown in Figure 5 indicates the predominant frequency as 2Hz.

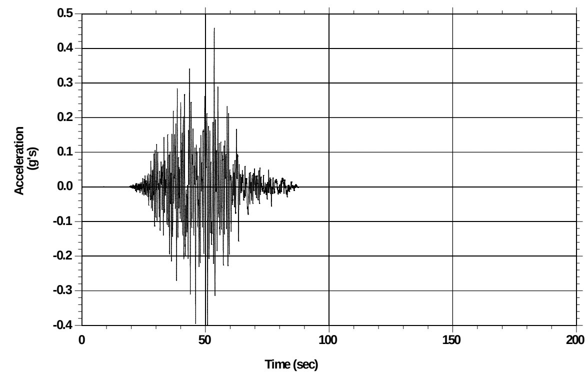


Fig. 4. Input acceleration time history obtained from DSHA

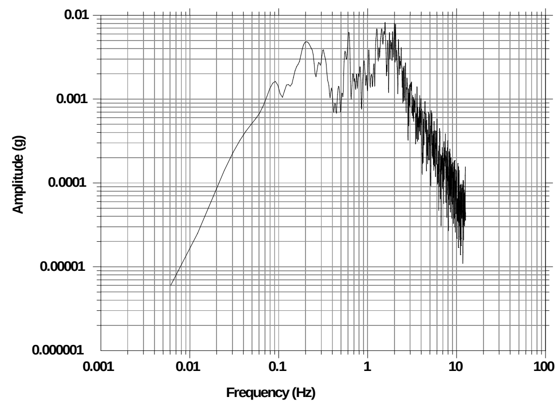


Fig. 5. Fourier spectra of input acceleration time history

The deconvolution analysis required to obtain the base motion from the known free surface motion is performed considering the average shear wave velocity profile of the region. The deconvolution analysis was performed using SHAKE 2000 to a depth of 60m and the base motion obtained (Figure 6) has a PGA value of 0.46g. The Fourier spectra of the base motion obtained from deconvolution analysis reveals a shift in the predominant frequency from 2 to 0.6 Hz as shown in Figure 7.

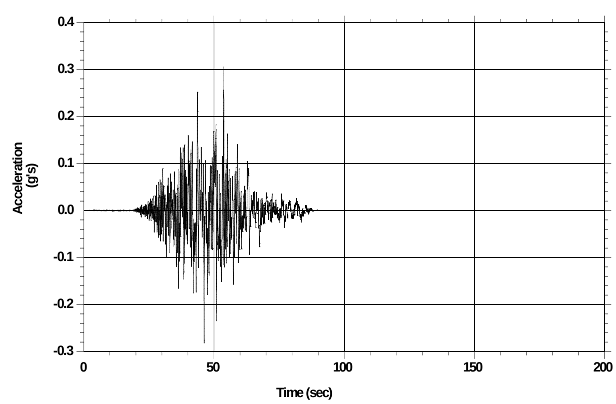


Fig. 6. Acceleration time history obtained from deconvolution analysis

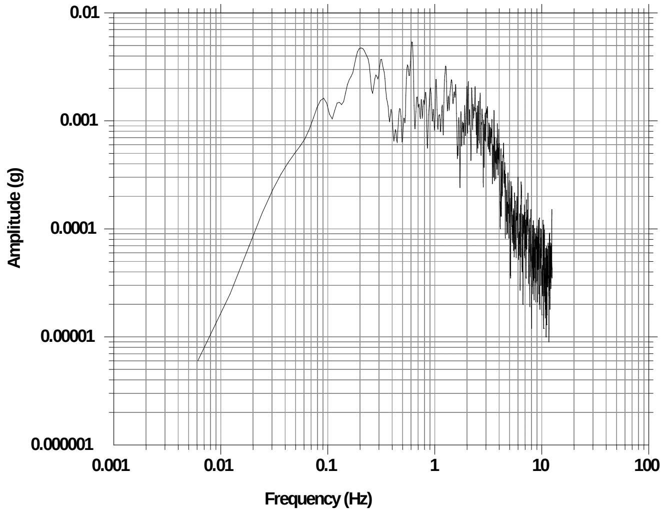


Fig. 7. Fourier spectra of the deconvoluted acceleration time history

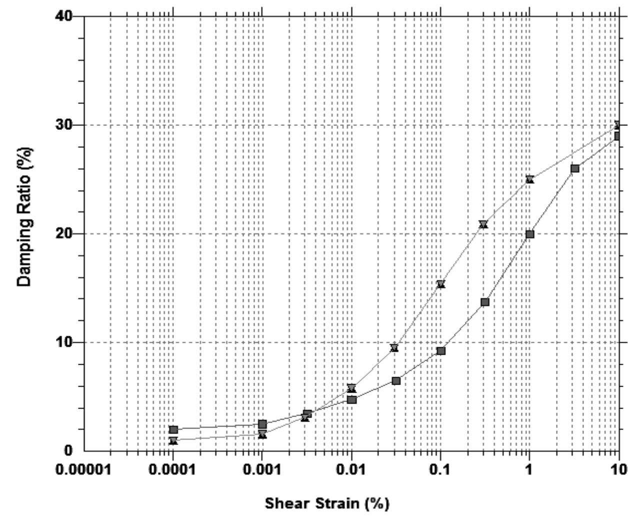
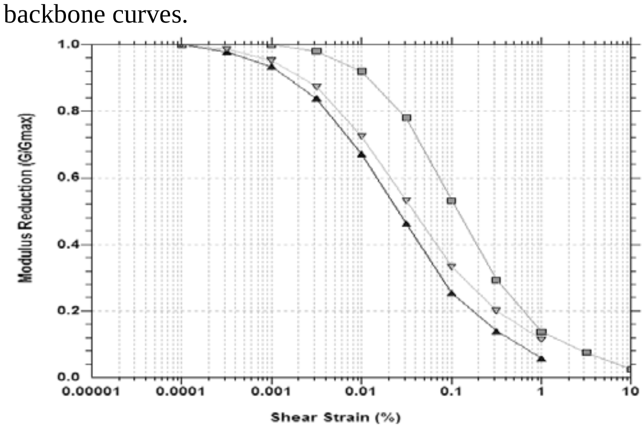


Fig. 8. Modulus reduction and damping curves used in SHAKE analysis

In the present study the ground response analysis is carried for the 60m thick soil strata. The layer is characterized by the unit weight of soil obtained from SPT data and shear wave velocity obtained from the seismic cross hole test data. The water table as observed is considered at a depth of 30 m below the ground level.

The nonlinear behavior of soil, reduction in stiffness and increase in the damping with increase in the shear strain, is accounted for by adopting modulus reduction and damping curves. In the SHAKE analysis the modulus reduction and damping curves are described at discrete points as proposed by Sun et al (1988) for sand and clay with plasticity index of 30% are selected based on the soil characteristics and confining pressure (Figure 8). The equivalent linear analysis was also performed using DEEPSOIL (Hashash, et al. 2009) adopting pressure dependant hyperbolic models (Hahash and Park, 2001). In this analysis pressure dependant hyperbolic model is fitted to the modulus reduction and damping curves proposed for sand (Seed and Idriss, 1970) and clay (Vucetic and Dobry, 1991). The target soil curves are fitted for both modulus reduction and damping curves, and the fitting parameters obtained were used to adjust the shape of the backbone curves.



GROUND MOTION PARAMETERS

The acceleration time history obtained at the surface by SHAKE and DEEPSOIL analysis are presented in Figure 9 and 10, respectively. It can be observed that both the methods predict amplification of the base motion at the same time period, however the surface PGA value obtained from SHAKE analysis (PGA = 0.52g) is 20% higher in comparison to the pressure dependant hyperbolic model (PGA = 0.43g) as expected. This is due to over damping of the system at higher strain levels (Chang et al, 1994). The Fourier spectrum for the surface acceleration (Figure 11 and 12) obtained by both the methods reveals predominant frequency range of 1.6 to 2.0Hz.

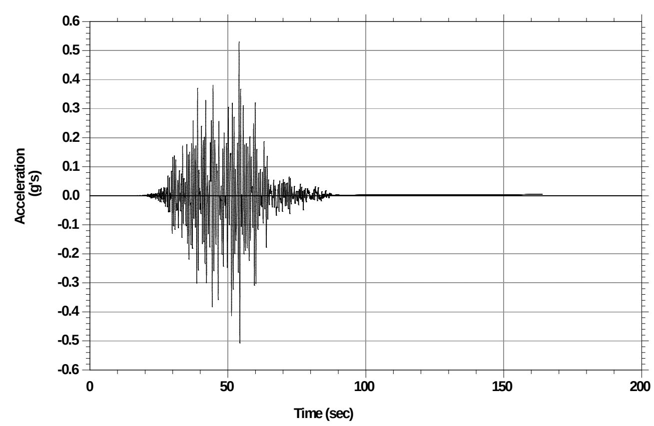


Fig. 9. Acceleration time history obtained from SHAKE analysis

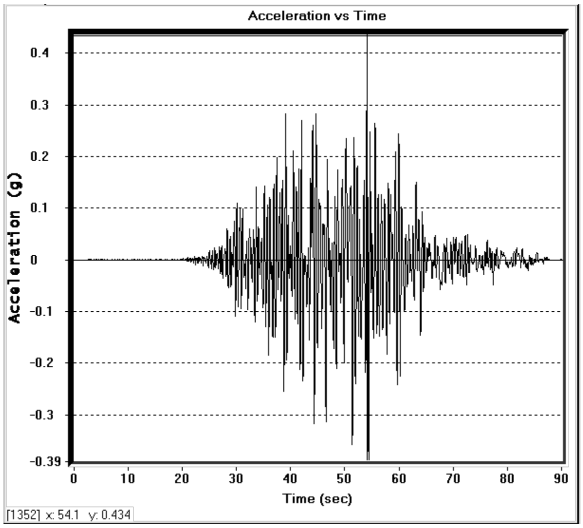


Fig. 10. Acceleration time history obtained from DEEPSOIL

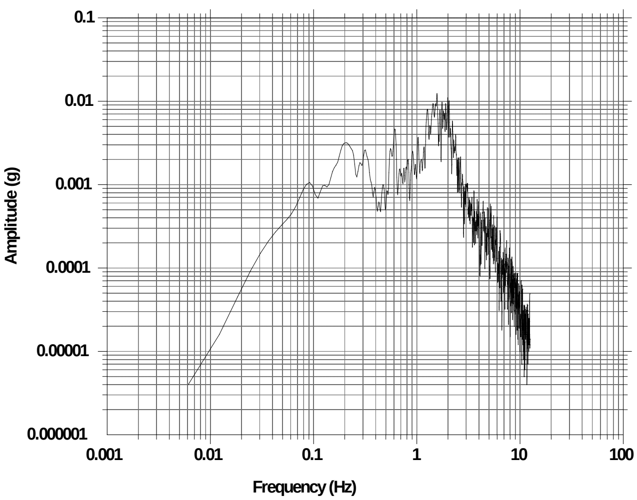


Fig. 11. Fourier spectra of the surface acceleration time history obtained from SHAKE analysis

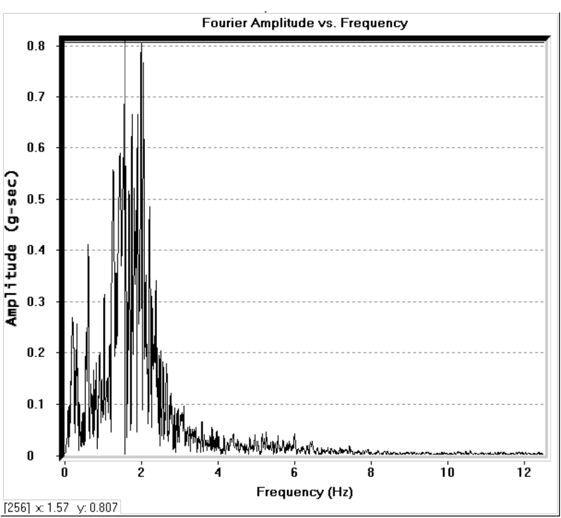


Fig. 12. Fourier spectra of the surface acceleration time history obtained from DEEPSOIL

The response spectrum obtained from SHAKE and DEEPSOIL analysis for different percentage of damping is presented in Figure 13 and 14 respectively. SHAKE analysis predicts higher spectral acceleration of 2.5g in comparison to 1.86g by modified hyperbolic model for the same time period of 1.6Hz for 5% damping.

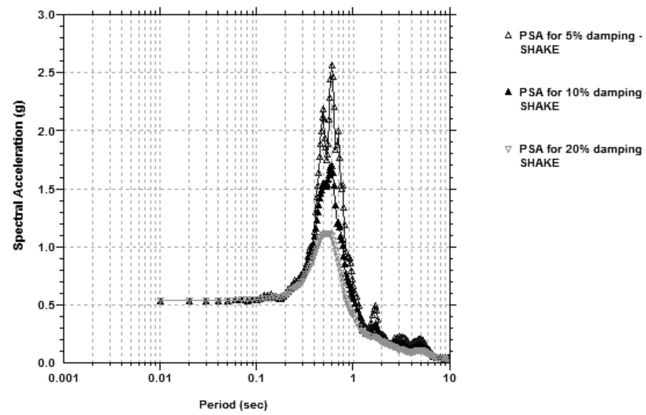


Fig. 13. Response spectrum at surface from SHAKE analysis

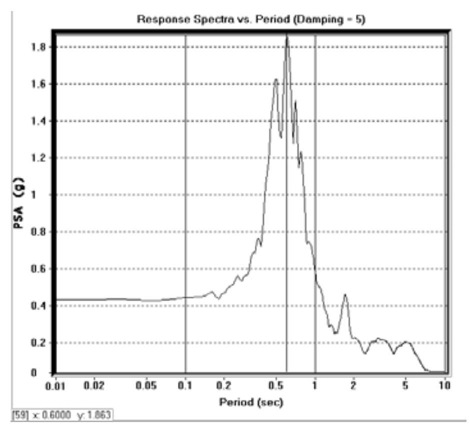


Fig. 14. Response spectrum at surface from DEEPSOIL

In the present study the Ratio of Response Spectral (RRS) analysis method (Jaramillo, 2006) is adopted to obtain the design response spectrum. The RRS analysis involves obtaining the spectral acceleration for the surface and the base motion, then dividing the surface spectrum by the base spectrum for each period. In the present case the surface spectra obtained from the ground response analysis covering the entire site is utilized to obtain the Ratio of the Response Spectra (RRS) curves as presented in Figure 15. The mean values of RRS curves are multiplied with the base spectrum to arrive the site specific spectra.

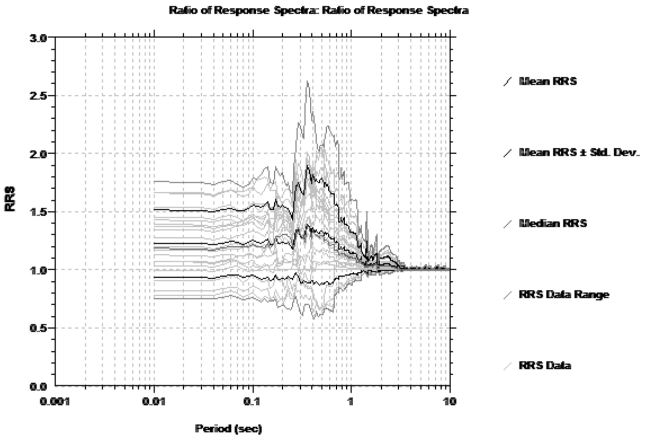


Fig. 15. Ratio of response spectra mean and median curves

In the present study the design response spectrum obtained from the ground response analysis (SHAKE 2000) is compared with the design response spectrum of various contemporary codes and attenuation relationships proposed for deep stiff soil sites. The spectral acceleration versus period plot (Figure 16) obtained from the RRS analysis is 16% higher than that proposed by the IBC design spectra for a site class D.

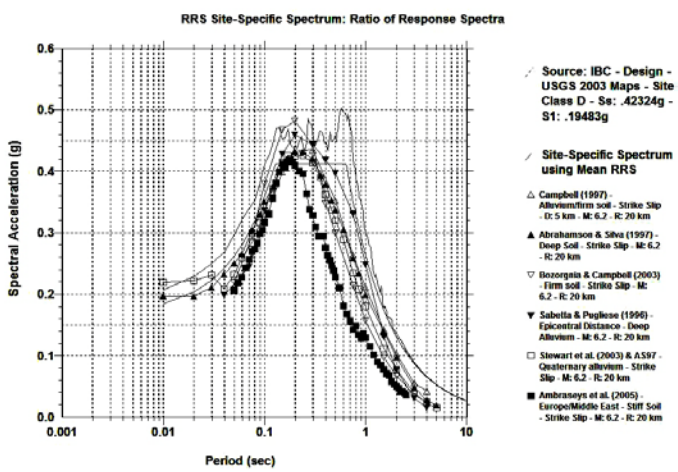


Fig. 16. Comparison of obtained spectral acceleration with IBC design spectra and other predictive relationships

The spectral acceleration obtained from the attenuation relationships proposed by Campbell (1997) for firm soil and Abrahamson and Silva (1997) for deep soil for an earthquake of Magnitude 6.2 compares approximately well with that obtained from ground response analysis in the lower – mid period range, however tends to under predict the spectral acceleration at the predominant site period (0.6 s). The predictive relationships proposed by Campbell and Bozorgnia (2003) for firm soil, Sabetta and Pugliese (1996) for deep alluvium, Stewart et al (2003) for quaternary alluvium, Ambraseys et al (2005) for stiff soils of Europe and middle east predicts similar spectral acceleration as that of the IBC (2003) for D class site at lower period and tends to under predict the spectral acceleration at mid and higher periods.

The normalized spectral acceleration versus period (Figure 17) obtained based on RRS analysis by using IS 1893 – 2002 design spectrum for medium soil as the target spectrum is compared with the normalized spectrum proposed by Dickenson and Seed (1994) for D class site, NEHRP (1994) D class site and UBC (1994) S2 site condition. Chang et al (1997) proposed design response spectrum for deep soil site based on the analysis carried out at the deep stiff soil deposits at Los Angeles during the 1994 Nigata earthquake.

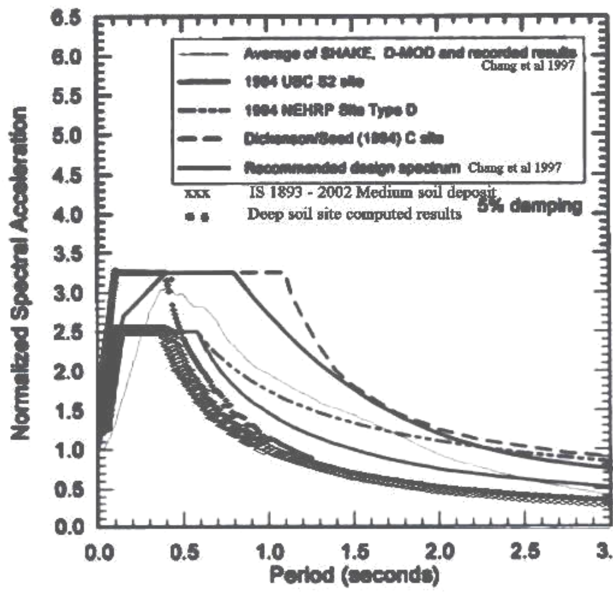


Fig. 17. Comparison of Normalized spectral acceleration obtained for different seismic provisions

It can be observed from the figure that the maximum spectral acceleration obtained from Dickenson and Seed (1994) and the design response spectrum recommended by Chang et al (1997) matches for the site considered, however the spectral acceleration curve obtained by the RRS analysis shifts towards the lower period in comparison to the recommended normalized spectrum for deep stiff soil sites. It is also observed that the contemporary codes (IBC, NEHRP and IS 1893) tend to under predict the spectral acceleration by about 30% at mid period range and predicts reasonably well in the low and high periods. This observation is in contrast to that observed by Chang et al (1997) for long period response, in which the seismic codes and 1D equivalent linear analysis tends to under predict the seismic response. Chang et al (1997) attributed the higher spectral acceleration to higher strength of the deep soil deposits which is capable of sustaining higher levels of shaking. The higher level of ground shaking is mainly attributed to the predominant period of the site (0.5 to 0.625 s), thus producing higher levels of shaking at the mid period range in comparison to several contemporary codes.

SUMMARY AND CONCLUSIONS

Site specific evaluation involving seismic hazard analysis and equivalent linear ground response analysis was performed for a deep stiff soil site, located on the Sabarmati river basin. The hazard level at the site was estimated by deterministic approach utilizing the Frankel predictive relationship (1996) considering the seismicity and seismotectonics within 250 km radius. The hazard analysis revealed the controlling source as the East Cambay fault with moment magnitude of 6.2 capable of causing a surface PGA of 0.46 g at the site. The strong motion data recorded at a site with identical site and seismic conditions during 1999 Chi-Chi earthquake was used as the input motion for performing deconvolution analysis for a depth of 60m. The shear wave velocity data obtained by conducting extensive cross hole tests at the site is used as an input to the ground response analysis. The site is generally classified as C class as per NEHRP 1994 provisions, C3 class as per Dickenson and Seed (1994) and Site class B as per Euro Code 8, based on the shear wave velocity profile in the top 30m. The ground response analysis for a depth of 60m was performed by equivalent linear analysis, in which the soil curves were defined at discrete points. The results of the analysis were compared with that obtained by using pressure dependant modified hyperbolic models to define the soil curves. The GRA using discrete point definition of the soil curve revealed spectral acceleration of 0.52g in comparison to 0.43g obtained using pressure dependant hyperbolic model. However both the analysis reveals a predominant frequency range of 1.6 – 2.0 Hz.

The site specific design spectrum developed using RRS analysis was compared with several contemporary codes and predictive relationships. In general it was observed that the seismic codes such as NEHRP (1994), UBC (1994), Eurocode 8 and IS 1893-2002 tends to under predict the maximum spectral acceleration at mid period range. The modified response spectrum proposed by Chang et al (1997) and the normalized spectrum proposed by Dickenson and Seed (1994) for deep stiff soil site predicted the maximum spectral acceleration exactly, however over predicted the seismic response at longer periods. Higher spectral acceleration is observed at the predominant site period in comparison to the seismic design provisions, which shall be revised accordingly.

It is concluded from the site specific analysis of deep stiff soil sites, that these sites do amplify the ground motion and are capable of producing sustained higher levels of shaking which is attributed to their higher stiffness and strength, Hence the study emphasizes the need for performing site specific seismic analysis for deep stiff soil sites also.

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